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OPTIMISATION OF THE CLIC POSITRON SOURCE*

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Abstract

In this report, we reoptimised the CLIC positron source at all collision energy stages. Simulation, optimisation algorithm and results were all improved compared with previous studies. Two different target schemes were studied and compared in terms of the advantages and disadvantages. The spot size of the injected electron beam was also optimised to achieve a compromise between large positron yields and safe energy deposition. The matching device for the capture of positrons was simulated and optimised with both improved analytic and realistic field maps. Conical aperture and front and rear gaps of the matching device were also considered for the first time. The optimised positron source is expected to have the lowest cost.

INTRODUCTION

The CLIC positron source [1] is used to produce high energy positrons up to 2.86 GeV. The positrons are then injected to the pre-damping ring (PDR) that is located downstream of the positron source. Positrons are supposed to be generated by high energy electrons impinging on a fixed tungsten target. An adiabatic matching device (AMD) is placed very close to the target to capture positrons with strong magnetic field. Positrons are further captured and accelerated to 200 MeV by the pre-injector linac which is composed of travelling wave (TW) structures and a 0.5 T surrounding solenoid. Finally the injector linac will accelerate the positrons from 200 MeV to 2.86 GeV.

Optimisation of positron source is not only helpful to reduce the required construction and operation costs, but also necessary to avoid damage to target and linacs caused by energy deposition. Positron yield is defined as the ratio of number of produced positrons to the number of injected primary electrons. Normally when primary electron energy is fixed, the accepted positron yield by the PDR is the figure of merit that needs to be maximised in the optimisation. However, for different primary energies, the primary beam power should be compared and optimised, instead of positron yield. A lower beam power usually means a lower cost. The peak energy deposition density (PEDD) is usually required to be less than 35 J/g [2] for safety reasons.

Simplified simulation and optimisation of the CLIC positron source have been studied in previous reports [3–5]. In this report, we improved the simulation and optimisation. The improvements that were ignored by previous studies basically include:

- Consideration of a conical aperture, fringe field and a reasonable shift of field peak for AMD simulation
- AMD simulation with not only an analytic field map but also a realistic field map from the design of AMD
- Simulation of the injector linac
- Consideration of reasonable distances between different sections
- A larger number of free parameters with a full-range optimisation.

Besides, a new simple and efficient optimisation algorithm [6] based on iterations of scan of free parameters was developed for positron sources and used in this study. The algorithm is introduced in a separate report and therefore not presented in detail in this report.

BEAM

GEANT4 [7] was used to simulate the generation of the primary electron beam and the target. In case of using crystal tungsten target, FOT [8] was used to simulate the channelling process for electrons. The phase spaces of primary electrons were generated by sampling with a gaussian function.

The emittance of the primary beam was optimised and suggested to be 80 mm·mrad, though positron yield was found to be independent on the emittance in a normal range. The primary electron energy was optimised and suggested to be 5 GeV, which is the same with the baseline value. Positron yield was found to be increased almost linearly as a function of the primary energy, but the beam power that normalised by the yield was not affected much by the energy. However the PEDD and deposited power in target can be significantly reduced by increasing the energy up to 5 GeV, while above 5 GeV the reduction of beam power, deposited power and PEDD is negligible.

The main primary electron beam parameters are summarised in Table 1. The spot size of the electrons was optimised and found to be different for different AMD simulations. Therefore it is not included in the table.

Table 1: Main Primary Electron Beam Parameters

Parameters	380 GeV	1.5 TeV and 3 TeV
Beam energy	5 GeV	5 GeV
Energy spread (RMS)	0.1%	0.1%
Normalised emittance (RMS)	80 mm·mrad	80 mm·mrad
Bunch length (RMS)	1 mm	1 mm
Number of bunches per pulse	352	312
Repetition rate	50 Hz	50 Hz

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The positron bunch population at the entrance of PDR was required to be 5.2×10^9 (~0.8 nC bunch charge) for the 380 GeV stage and 3.7×10^9 (~0.6 nC bunch charge) for the 1.5 TeV and 3 TeV stages [9]. An additional 20% safety margin has also been considered in our study.

TARGET

In previous studies and baselines for the CLIC positron source, a hybrid target was proposed to be used as it was found to be able to reduce the PEDD significantly. The hybrid target is composed of a thin crystal tungsten target and a thick amorphous tungsten target, with a long distance between them. In order to reduce energy deposition in the target, a dipole magnet with strong magnetic field was used to deflect and remove charged particles from the crystal target, leaving only photons to impinge on the amorphous target.

A preliminary optimisation of the positron yield shows that the accepted positron yield was reduced significantly by the long distance between the hybrid targets, and the maximum positron yield was achieved only when the distance was zero. This is due to that on one hand the long distance of the hybrid target increased the photon and positron beam sizes, and on the other hand the charged particles (mainly remaining electrons taking ~40% of primary beam power) removed by the dipole could also contribute to the positron production.

Nevertheless, the study of hybrid target scheme is still in progress as it is thought to have the advantages of reduced and safe PEDD and thermal load in the target. Therefore in this study the conventional target scheme with a single amorphous tungsten target was adopted. The thickness of the amorphous target was optimised to be 18 mm.

ADIABATIC MATCHING DEVICE

RF-TRACK [10] was used to simulate the AMD and pre-injector linac. Different magnetic field maps were used and optimised for the AMD:

- An analytic on-axis field map assuming a conical inner aperture increased linearly along the longitudinal coordinate.
- A realistic 2D field map from flux concentrator (FC) simulation using the OPERA software with a conical inner aperture that is linearly increased.
- An alternative realistic 2D field map with a similar but not linearly increased FC inner aperture. The peak field is lower than linear-shaped aperture, but it allows to technically reduce the voltages, forces and power supply effectively [11].

The field maps were optimised and compared in Fig. 1. For technical considerations, the peak fields were limited to be no larger than 6 T. The fringe field in target was also considered, though its impact on final results was found to be negligible.

It was found that the positron yield was reduced obviously with a larger gap between the target and the AMD. In our study, it was fixed to 2 mm which is thought to be technically

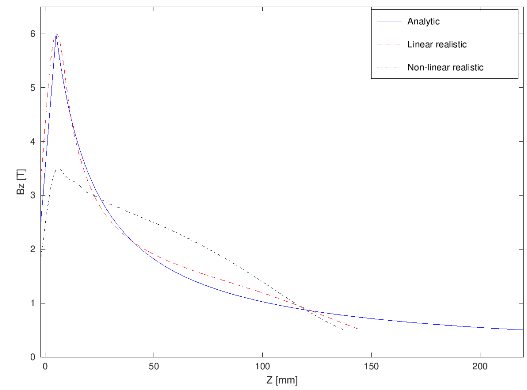

Figure 1: Comparison of different AMD on-axis field maps. The front surface is at $z = 0$ mm.

accepted. In case of analytic AMD simulation, the optimised length and entrance aperture were limited to 22 cm and 8 mm respectively.

The optimised on-axis peak field is 6 T for the analytic AMD simulation and the realistic AMD simulation with a linear-shaped aperture at all energy stages. For the realistic AMD simulation with a non-linear aperture, the optimised peak field is 3.5 T for the 380 GeV energy stage and 4 T for the 1.5 TeV and 3 TeV stages.

The optimised spot sizes of the primary electrons are summarised in Table 2, for different AMD simulations and energy stages.

Table 2: Optimised Primary Electron Spot Size

Spot Sizes	380 GeV	1.5 TeV and 3 TeV
Analytic AMD	2.2 mm	1.5 mm
Linear realistic AMD	2.3 mm	1.5 mm
Non-linear realistic AMD	2.8 mm	1.8 mm

PRE-INJECTOR LINAC

The TW structures work in the $2\pi/3$ mode, with a frequency of 2 GHz and an aperture of 20 mm radius. 11 structures were used to accelerate positrons to 200 MeV, while the first structure was supposed to capture positrons with deceleration. Each TW structure is 1.5 m long, composed of 30 cells.

The distance between the AMD and the TW structures was optimised and suggested to be 50 mm, though positron yield was found to be independent on the distance. The distance between the structures is suggested to be 20 cm. It was found that an increase in the distance between the first two strcutures would reduce the positron yield significantly, especially for a distance larger than 20 cm. The distances between other structures would not affect the positron yield.

The TW structures are surrounded by a DC solenoid with a constant 0.5 T magnetic field. It was found to be possible to improve the positron yield by ~25% with a larger solenoid

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field of ~0.8 T. However it is thought to be difficult to achieve such a high field technically for L-band structures.

The phases and average gradients of the TW structures were optimised to make sure that the mean energy of positrons is close to the designed energy of 200 MeV at the pre-injector linac exit. The phases are actually kind of arbitrary and usually internally used, as it depends on how the reference particle is defined. The decelerating and accelerating gradients for the analytic AMD simulation are 13 MV/m and 17 MV/m respectively. For the realistic AMD simulation with a linear-shaped aperture, the gradients are 20 MV/m and 19 MV/m, while with a non-linear aperture, the gradients are both 20 MV/m.

INJECTOR LINAC

PLACET [12] was used to simulate the injector linac. A recent design [3] of the CLIC injector linac was adopted in our simulation. In the new design, the injector linac was optimised and simplified with a removal of the bunch compressor and a reduction of the number of quadrupoles. The injector linac is composed of five different FODO sections. The same RF structures with the pre-injector linac were used to accelerate the positrons. The distance between quadrupoles was increased along the acceleration beam line. As a consequence the RF structures in the first two FODO sections were surrounded by quadrupoles. To have a good transport of the beam, additional matching quadrupoles were needed for each section. The total number of quadrupoles used in our study is 143, with 16 of them being used for the matching purpose.

The acceptance of the PDR was considered by applying a window cut on the energy and time of positrons arriving at the injector linac exit. The energy acceptance is within ±1.2% of the desired energy, 2.86 GeV, while the total size of time window is 20 mm/c. The longitudinal phase space of the positrons at the end of the injector linac for the realistic AMD simulation with a linear aperture is presented in Fig. 2, with the energy and time window displayed by a red rectangle on the plot.

The acceleration of positrons in the injector linac up to 2.86 GeV was simplified in the optimisation by an analytic calculation: $\Delta E = \Delta E_0 \cdot \cos(2\pi f \cdot \Delta t)$. In the formula, $\Delta E_0 = 2.86\,\mathrm{GeV} - E_{\mathrm{ref}}$ is the maximum energy gain for the reference particle, $f = 2$ GHz is the RF frequency and $\Delta t = t - t_{\mathrm{ref}}$ is the time difference from the reference particle. The reference particle with an energy around 200 MeV was defined such that the mean energy of positrons accepted by the PDR was exactly 2.86 GeV and the accepted positron yield was maximised.

RESULTS

The final simulation results, including the accepted positron yield by the PDR, normalised PEDD and deposited power in the target and normalised primary electron beam power, are summarised in Tables 3 and 4, respectively at the 380 GeV energy stage and the 1.5 TeV and 3 TeV energy stages. The PEDD, deposited power and primary beam power are normalised to the required bunch charge and number of bunches by the accepted positron yield at the entrance of the PDR.

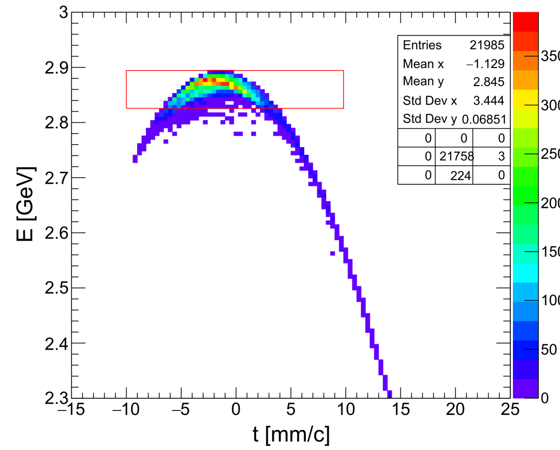

Figure 2: Longitudinal phase space of the positrons at the end of the injector linac for the realistic AMD simulation with a linear aperture. Energy and time cut window are displayed by a red rectangle on the plot. Reference time is set to 0.

Table 3: Final Results at the 380 GeV Stage

Results	Positron Yield	PEDD	Deposited Power	Beam Power
Analytic AMD	2.15	32.2 J/g	11.2 kW	40.8 kW
Linear realistic AMD	1.91	33.0 J/g	12.6 kW	45.9 kW
Non-linear realistic AMD	1.31	33.5 J/g	16.3 kW	67.2 kW

Table 4: Final Results at the 1.5 TeV and 3 TeV Stages

Results	Positron Yield	PEDD	Deposited Power	Beam Power
Analytic AMD	2.50	31.7 J/g	6.1 kW	22.2 kW
Linear realistic AMD	2.42	32.7 J/g	6.3 kW	22.9 kW
Non-linear realistic AMD	1.76	32.5 J/g	7.7 kW	31.4 kW

SUMMARY

In this report, we have improved the simulation and optimisation of the CLIC positron source. The optimised positron source is supposed to achieve the lowest cost. The simulation of AMD was significantly improved by using realistic apertures and field maps. The injector linac was also simulated with the latest design. A large number of parameters for different positron source sections have been optimised and discussed in detail. The target was simulated with the conventional single amorphous target scheme for its advantage of high positron yield. The study of an alternative hybrid target scheme is still in progress with potential benefits of reduced PEDD and thermal load but also with a significantly reduced positron yield. Final optimised results are given for different AMD simulations at different energy stages.

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